Assessing the Impact of Development Disruptions and Dependencies in System-of-Systems

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EXECUTIVE SUMMARY

Our work in RT-155 has continued tool development of the System of Systems Analytic Workbench (SoS-AWB) and transitional activities with key collaborators. The tools include: System Operational Dependency Analysis/System Developmental Dependency Analysis (SODA/SDDA), Multi-Stakeholder Dynamic Optimization (MUSTDO), System Importance Measures (SIMs), and Robust Portfolio Optimization (RPO).

The workbench provides a means of addressing SoS practitioners' 'archetypal questions' in scenarios where size and/or interdependencies between systems are high. The workbench also enables analysis of capability and risk during the conduct of SoS evolution. Our common use case demonstration problem involves a Naval Warfare Scenario (NWS) that is based on the architecture of the Littoral Combat Ship (LCS). Each of the tools has used this common case study to illustrate the value in each tool performing various types of SoS level architectural analysis, as evidenced by prior literature and extensive documentation for predecessor RT-36, RT-44b, RT-108, and RT-134 tasks.

SUMMARY OF RT-155 ACHIEVEMENTS

While continuing research on each of the methods, our FY16 effort emphasized transitioning of the AWB for test in practical settings with our key collaborators, and dissemination to the broader community. Our efforts have resulted in the following areas of coordination and dissemination (details of these have been documented in RT-155 bi-monthly reports):

Output	Description of Dissemination
Conference Publications	**CSER 2017** "A robust portfolio optimization approach using parametric piecewise linear models of system dependencies" 15th Annual Conference on Systems Engineering Research (CSER), Redondo Beach, CA, March 23-25, 2017 [accepted] **IAC 2016** "Understanding Human Space Exploration" 67th IAF International Astronautical Congress Guadalajara, Mexico, 26-30 Sept 2016 – [recommended by conference committee for publication to Acta Astronautica]
Journal Publications	**IEEE Systems** "Multi-Stakeholder Dynamic Optimization for Acknowledged System-of-Systems Architecting" [submitted] **Research in Engineering Design** Guariniello, C., DeLaurentis, D., "Supporting design via the System Operational Dependency Analysis methodology", Research in Engineering Design Vol.28 (2017), pp. 53-69 **Systems Engineering** Resilient System-of-System Design using System Importance Measures, [Will prepare for submission]
Webinar /Panels	SoSCIE webinar, Center for Education and Research in Information Assurance and Security (CERIAS)

Extension of SoS-AWB Methodologies

We have extended each tool in the SoS-AWB and refined them through our exchanges with collaborative partners. Primary changes and value added in the methods of the SoS-AWB involves the following:

1. *Combined RPO-SODA method* – We have integrated the network interdependency modeling capabilities of SODA within the portfolio optimization construct of the RPO—this involved mathematical modeling development of necessary equations that can explicit introduce SODA'S piece-wise linear construct within RPO. Theoretical details and an example application are included in our publication titled "*A robust portfolio optimization approach using parametric piecewise linear models of system dependencies*" which we will present at the CSER 2017 conference. We have included a demonstrative version of the joint framework for execution through the RPO GUI interface.

2. *MUSTDO* – Extended and validated the mathematical formulation of optimal transfer contract scheme being used within MUSTDO; Explored practical interpretations of the transfer contract concept.

3. *SIMs* -Validated existing framework with an improved ABM simulation and improved existing resilience map to better reflect critical systems and potentially effective mitigations.

4. *SODA/SDDA* – Added ability to model cyclic networks (SODA). Added ability to include external factors (SDDA)

ENGAGEMENT/INTERACTION SUMMARY

SERC- We have continued our collaborative exchanges with various members of SERC community as and when needed towards development and/or dissemination of the SoS-AWB.

MITRE- We have had detailed exchanges with personnel at MITRE on use of the SoS-AWB toolset for internal cases run locally at MITRE. The interactions were with MITRE members: (Laura Antul, Ryan Jacobs, Matt-Cotter and Aleksandra Markina-Khusid) and leads: (Dr. Judith Dahmann and Tom Wheeler). Interactions involved primary adaptation of SODA and RPO toolset for application on internal case problems to MITRE environment.

Johns Hopkins University Applied Physics Laboratory (JHUAPL) – Transition of SERC Analytic Workbench Technology into Government Service by JHUAPL. The application effort involves modeling an existing messaging network to perform real-time situational awareness. The Analytical Workbench's combination of dependency metrics (strength, criticality, and impact) will be leveraged within their own model of system effectiveness to measure network performance in real-time. These models will then be linked to a visualization/dashboard system that will allow operators to quickly and graphically determine consequences to related components based on the dependencies. We have attached the *JHUAPL-SERC-Article.pdf* that covers the scope of technology transfer for the SoS-AWB.

Naval Surface Warfare Center Dahlgren Division (NSWCDD)-

With our CRADA finalized with Navy NSWCDD, we made substantial progress (with Dahlgren POC Mary Ann Cummings), including the following:

- Detailed technical exchanges and demos to establish understanding and requirements for use of the SoS AWB at NSWCDD.
- Developed SoS-AWB in accordance with exchanges, resulting in software being shared with NSWCDD (POC: Adam Bahrainwala). *More specifically, Adam Bahrainwala demonstrated use of internal simulation based data being used in tandem with SODA toolset for interdependency analysis.*

NASA Marshall Space Flight Center - Cooperative agreement in place to use methods in SoS-AWB (RPO, SODA, SDDA) to analyze space exploration architectures.

Software Dissemination and NanoHub Deployment

We have made prototype version of our tools available through the *nanohub.org* portal, hosted at Purdue University. The team worked on the development and compilation of tools for the hub environment, including necessary edits to relevant toolsets and GUI interfaces, to facilitate compatibility in this hosted environment. We have **60 users thus far, with a total of ~700+ runs of the SoS AWB.** (Please see attached file: nanohub-usage.pdf for global usage report and simulation runs statistics of our toolset).

The tool is open to the public and users can sign up for a free account at *nanohub.org* to access the *System of Systems Analytic Workbench* set of tools. Additionally, we are delivering an updated copy of our software to the DoD SERC, in accordance with the terms of our statement of work.

In summary, we have made progress in refining methods/fixing bugs through interactions with collaborator entities using demonstrative versions of our SoS AWB. Further, we see continued use of the online version of our toolset as evidenced by the published statistics. Our transitional and collaborative activities with MITRE Corporation, Naval Surface Warfare Center Dahlgren Division (NSWCDD) and Johns Hopkins University Applied Physics Laboratory (JHUAPL) have been successful in that the respective collaborators have demonstrated use of the Purdue SoS-AWB in native environments. As of this report, we are in the middle of executing an official technology transfer of IP (limited) to JHUAPL, in accordance with relevant RT-155 contract agreement clauses.

I. ***Guide to the Various Products attached to the Summary Final Report***

- Papers
  - *SODA_RIED.pdf - Supporting design via the System Operational Dependency Analysis methodology* - Journal paper, published in Research in Engineering Design.
  - *MUSTDO_Methodogy_UnderReview.pdf* – Draft paper, submitted for consideration to IEEE Systems journal
  - *IAC-16-A3.19.pdf* – Paper published at IAC 2016 conference on SODA methodology and application

- Code documentation
  - *SODA_GUI_Manual.docx*: description of the Graphic User Interface for SODA analysis, including possible inputs, choice of methods, resulting plots, output files.

- *SDDA_GUI_Manual.docx*: description of the Graphic User Interface for SDDA analysis, including possible inputs, choice of methods, resulting plots, output files.
- *RPO_Manual_New_Version.docx:* description of Graphic User Interface for Robust Portfolio Optimization toolset, including required inputs, choice of methods, output numbers and plots and other pertinent information.
- *MUSTDO_GUI_Manual.docx*: description of the Graphic User Interface for MUSTDO framework, including possible inputs and resulting plots.
- *SIM_GUI_Manual.docx*: description of the Graphical User Interface for SIM framework, including required inputs, analysis methods, type of outputs and other definitions.

- Technical Summaries of Methods:
  - A technical summary of methods, processes and tools in the SoS-AWB is given in the SERC Sponsor Research Review RT-155 slides as attached to this report. (Purdue-RT-SSRR-2016-Final.pdf)

FUTURE PLANS

Our work in this RT-155 effort has presented value added to our key collaborators and the broader community. We have engaged SERC on a path forward for further transitional activities and are, at the time of this report being generated, proposing follow-on transitional activity and development work under the auspices of a new RT-178 effort.